SMART WEAPONS OPERABILITY ENHANCEMENT
USAF
ARMY NAVY
DARPA
SWOE

# A REVIEW OF MILLIMETER WAVE MODELING

Kevin O'Neill

U.S. Army Cold Regions Research
and Engineering Laboratory
Hanover, NH



SWOE Report 93-1
May 1993

# A REVIEW OF MILLIMETER WAVE MODELING

Kevin O'Neill

U.S. Army Cold Regions Research
and Engineering Laboratory
Hanover, NH



SWOE Report 93-1
May 1993

## FOREWORD

SWOE Report 93-1, May 1993, was prepared by Dr. K. O'Neill of U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

This report is a contribution to the Smart Weapons Operability Enhancement (SWOE) Program. SWOE is a coordinated, Army, Navy, Marine Corps, Air Force and DARPA program initiated to enhance performance of future smart weapon systems through an integrated process of applying knowledge of the broadest possible range of battlefield conditions.

Performance of smart weapons can vary widely, depending on the environment in which the systems operate. Temporal and spatial dynamics significantly impact weapon performance. Testing of developmental weapon systems has been limited to a few selected combinations of targets and environment conditions, primarily because of the high costs of full-scale field tests and limited access to the areas or events for which performance data are required.

Performance predictions are needed for a broad range of background environmental conditions and targets. Meeting this need takes advantage of significant DoD investments by Army, Navy, Marine Corps and Air Force in 1) basic and applied environmental research, data collection, analysis, modeling and rendering capabilities, 2) extensive target measurement capabilities and geometry models, and 3) currently available computational capabilities. The SWOE program takes advantage of these DoD investments to produce an integrated process.

SWOE is developing, validating, and demonstrating the capability of this integrated process to handle complex target and background environment interactions for a world-wide range of battlefield conditions. SWOE is providing the DoD smart weapons and autonomous target recognition (ATR) communities with a validated capability to integrate measurement, information base, modeling and scene rendering techniques for complex environments. The result of a DoD-wide partnership, this effort works in concert with both advanced weapon system developers and major weapon system test and evaluation programs.

The SWOE program started in FY89 under Balanced Technology Initiative (BTI) sponsorship. Present sponsorship is by the U.S. Army Corps of Engineers (lead service), the individual services, and the Joint Test and Evaluation (JT&E) program of the Office of the Director of Defense Research and Engineering (DDR&E), Office of the Secretary of Defense (OSD).

The Program Director is Dr. L.E. Link, Technical Director of the U.S. Army, Cold Regions Research and Engineering Laboratory (CRREL). The Program Manager is Dr. J.P. Welsh, CRREL. The Integration Manager is Mr. Richard Palmer, CRREL. The task areas and their managers are as follows: Modeling Task Area, LTC George G. Koenig, USAF, Geophysics Laboratory (GL), of the Air Force Phillips Laboratories; Information Bases Task Area, Mr. Harold W. West, PE, U.S. Army Engineer, Waterways Experiment Station (WES); Scene Rendering Task Area, Mr. Mike Hardaway, Corps of Engineers, Topographic Engineering Center (TEC); Validation Task Area, Dr. Jon Martin, Atmospheric Sciences Laboratory (ASL) of the Army Materiel Command.

# I. INTRODUCTION

This report conveys the results of a survey undertaken for the Smart Weapons Operability Enhancement (SWOE) Program. Its aim is to review the state of the art of millimeter wave (MMW) modeling for scattering, emission, and propagation/absorption in the environment, particularly in the spectral vicinity of 35 and 94 GHz. Where possible, models are to be evaluated in terms of validity and utility, with recommendations for the direction of future attention and possible R&D support. In this context, "model" means a theoretical formulation that is derived from first principles, such as Maxwell's equations or conservation of energy, and that is incorporated in a tractable computational vehicle. The ultimate purpose for identifying, collecting, and integrating an ensemble of such models is to generate energy field distributions, i.e. scenes, that sensors might confront under the widest possible variety of conditions. It is for the sake of this generality that models were sought based as much as possible on first principles, with minimal reliance on empirical or arbitrarily tunable parameterization.

Truly useful models should be simple and accessible enough so that users other than the originators can run them. This requirement strains against the constraint of generality and first-principles validity. Due to the nature of the field, we may find in many instances that the most rigorous models, or perhaps the only rigorous models, are ensconced in sophisticated research structures. These may require advanced, specialized knowledge, extremely complex, difficult to obtain input data, and intolerably massive computational resources. At least in extreme instances of this sort, such models cannot be pursued here for the ultimate scene generation purposes. At the same time, the tension between generality and validity on the one hand and simplicity and accessbility on the other may force a degree of compromise in the prioritization of models. The requirements of rigor may have to be relaxed in some cases; in others utility may be achieved only by following an ongoing development or working with model originators over an extended period.

The specific information incorporated in this survey is derived from a variety of sources: personal knowledge of the author and information direct from the open literature (An Annex to this report contains copies of most of the references listed in Section V); discussion and communication with various recognized modelers; response of modelers to a questionaire; and a workshop held on May 13 - 15, 1992 for a general review and discussion of MMW modeling capabilities. A list of workshop participants appears in the Appendix below. Beyond the specific list of topics for the workshop sessions, far ranging discussions took place to establish the boundaries and content of the current state of the art. In soliciting information and taking note of models for this report, as much emphasis as possible was placed on importance of successful model verification as a selection criterion. In this context, "verification" includes all testing and validation, including comparison of computations to common knowledge expectations or limits imposed by basic physics; comparison to "exact" numerical solutions; or qualitative and quantitative comparison to physical measurements.

For the purposes of surveying models of MMW propagation, scattering and emission we might sort them according to three kinds of consideration:

1. Model type: physical process and basis, approach, methods and techniques used
2. Applications: media considered and validation
3. Computer codes: packages and their originators.

For the ultimate purpose of scene generation we must deal in the end with item #3. Existing, facilitated, documented programs are sought. Ideally these should be in integrated, modular packages, but single programs are also of interest if they pose no insurmountable problems to integration in larger ensembles in standard languages. The codes must be directly accessible, in the public domain or easily available for a modest cost, and should ideally be accompanied by the prospect of continuing support. Thus

our ultimate constraints give a certain prominence to producers and active disseminators of finished software vehicles. At the same time it is recognized that the physical problems we are addressing are extremely difficult. There is no well established corps of valid, recognized, elaborated computer packages as in some other areas, e.g. structural analysis or heat transfer. Inevitably, the models we desire are typically being generated at the frontiers of research as pursued at the most advanced research institutions. For the most part, these institutions have neither the resources nor the mandate to produce polished software for dissemination. We recognize also that when energy has been devoted substantially to software polish and dissemination, scientific rigor may have been left a bit behind. Therefore, if our ultimate demand is for generality and fidelity to nature, we must also devote attention to models that are in some intermediate or even early stage of development as far as computer code is concerned. In the very least, doing so provides valuable perspective on the more available packages.

Prior to consideration of specific codes, item #2 is our most basic sorting category for review. This is because we are asking <u>what</u> features we are able to model for inclusion in a generated scene. Fallen and falling snow, fresh and saltwater ice, bare soil, vegetated soil, vegetation canopy, clouds and rain...? While the availability of codes may determine our options in the end, it is the need to model particular media and configurations that drives both our quest for codes as well as our drive to develop new methods. The bulk of what follows (Section III) will therefore be organized along the lines of item #2.

Item #1 provides the broadest and most far-reaching terms in which to consider the field. Various general approaches are applied in models of substantially different media. The same general types of models also appear in numerous different computer codes. Therefore we begin what follows with the briefest subsection as an overview of item #1.

In summary thus far: we converge on item #3 by passing through items #1 and #2. Some published models were eliminated at the outset because they fail in some serious way to meet one or more of the selection criteria explained above. For reasons explained in the preceeding discussion, Sections II and III below include items that fail in one or another way to meet our criteria ideally but which have distinct value. Ultimately, in Section IV, a subset of the models considered first in terms of items #1 and #2 is presented in terms of specific available computer programs or packages.

# II. METHODS AND APPROACHES

## II.1 VOLUME SCATTERING

In essentially all applications of interest here, some type of randomness must be considered. For volumes the randomness has been included either by assuming that 1) dielectric properties vary continuously, with a zero mean fluctuating term added to the average permittivity, or 2) dielectric properties have a discrete distribution, i.e. certain step changes in value occur across boundaries of discrete embedded elements. Idealized representative elements are often assumed, e.g. dielectric discs, spheroids, cylinders, etc., possibly with statistical distributions of size, shape, or orientation. The simple sum of contributions from individual elements may suffice to compute the response when the medium is diffuse, as in an aerosol. For denser media, interactions between the elements must be included increasingly. In the limit of very dense media with a great deal of contact between elements or with continuous, tortuous intermixed phases, it may no longer be a promising approach to regard the medium in terms of contributions from discrete elements. The distinction between continuous medium and discrete scatterer theory is somewhat misleading, in that the former can generally deal with discrete scattering elements as well. One merely specifies a discrete permittivity distribution and performs much the same computational motions as for a continuous distribution, ending up with essentially the same statistical descriptors for the medium as under the discrete scatterer approach. In either case, one must integrate the statistical medium description into a set of equations covering the medium as a whole, and the principle approaches have been via analytical wave theory (WT) and radiative transport theory (RT).

The perceived difficulty of applying wave theory to an extremely complex mixture has appalled some authors up through the present to the extent that the WT approach is sometimes dismissed out of hand. Nevertheless, the brave beginnings of its recent incarnations in the early 80's have been followed by the undaunted into formulations of ever greater sophistication (e.g. Nghiem

et al, 1990; Nghiem, 1991). In principle WT can include all multiple scattering, diffraction, and interference effects. In practice it is limited by the difficulty of formulating the characteristics, behavior, and distribution of constituent elements and then solving equations incorporating their interactions. Green's function based integral equations are generally used. Perhaps the simplest method for making the integral equations tractable is the Born approximation. This has been used for increasingly complex configurations in recent years, e.g. an isotropic-anisotropic three layer system with rough surface (Borgeaud et al, 1986). The Rytov and Foldy approximations are also applied to extend the range of validity or tractabilitiy. The distorted Born approximation extends the WT density and fluctuation strength range further, particularly in conjunction with strong fluctuation theory. Recently dense media formulations have been advanced for media with particle size distributions, employing the quasicrystalline approximation (QCA) and QCA with coherent potential (QCA-CP) and pair distribution functions (Ding and Tsang, 1991; Tsang and Kong, 1992). Whatever the current (evolving) limitations on density (volume fraction) and on particle size relative to wavelength, we note that important links have been made between simulations based on dense media theory and Monte Carlo calculations, in effect verifying each. The latter have the advantage that true solutions of Maxwell's equations may be obtained, including coherent interactions, and nó adjustable parameters are introduced. Dense media theory calculations have agreed well with Monte Carlo calculations of extinction rate for volume fractions up to 25% (Tsang et al, 1992b); they have also agreed well with laboratory data where input parameters were derived from measurement (Ishimaru and Kuga, 1982; Wen et al, 1990).

In the RT approach it is assumed that interacting field components are sufficiently uncorrelated so that addition of power as opposed to addition of fields holds. Thus an energy balance equation is formulated in terms of specific intensity, in scalar form for completely unpolarized fields or in vector form in the sense that the (modified) Stokes vector is the dependent variable when polarization is important. Maxwellian underpinnings may reside in diffraction and interference effects expressed for behavior of constituent elements in the medium. However these are ultimately swallowed up through

the phase and extinction functions (matrices) in the intensity-based governing equation. Comprehensive introductions to RT are provided by a number of recognized sources (Chandrasekhar, 1960; Ishimaru, 1978; Tsang et al, 1985; Ulaby et al, 1986). As in the WT approaches, researchers have built increasingly complex and diverse scattering elements into the medium formulations, treating increasingly complex shapes and distributions of scattering elements and media. Although complex media descriptions may be built into RT formulations more easily than for WT, numerical solution can still be daunting. Iterative methods are sometimes used, though they are suited primarily to sparse or weakly scattering media and are rarely carried beyond the second order. Kuga (1991) reports a system that provided 3rd and 4th order iterations and which compared well with "exact" numerical solutions obtained with the discrete ordinate method. While the method requires low density and spherical particles, it can deal with large particles. Rough surfaces have been included in WT approaches simply by incoherently adding the independently calculated volume and surface scatter (e.g. Borgeaud et al, 1986), though this does not take the volume - surface interactions fully into account. In RT, rough surface effects can be included completely consistently, at least in principle, by modifying the boundary conditions; in general RT can more easily handle complicated configurations and media profiles than the WT.

The deficiencies of conventional or "classical" RT are also to be noted. Its basis is less rigorous than WT. Phase information is generally absent and coherent effects such as enhanced backscatter cannot be predicted. Other coherent effects associated with layer bottom boundary reflections are also not included. This may not be so important at MMW frequencies in instances when strong attentuation occurs such that lower boundaries may have little effect on measurements from above. Also, the underlying lack of correlation assumed in RT for the interaction of fields associated with medium elements breaks down for sufficiently dense media. These shortcomings have given rise to recent formulations designed to include some coherent effects. Tsang and Ishimaru (1987) have introduced the radiative wave equation approach to RT, and the modified radiative transfer approach (MRT) has sought to include some coherent effects since the late 1970's (e.g. Tsang and Kong, 1976; Zuniga and Kong, 1980) with recent developments for more complicated media (Lee and

Kong, 1988; Lee and Mudaliar, 1988; Mudaliar and Lee, 1990). While the MRT equations are ultimately of the same form as traditional RT equations so that similar solution methods may be employed, the greater complexity of the MRT appears to limit its applicability at present. While the emphasis in the above references has been on active remote sensing, this should not obscure the prominence of RT for addressing passive observations of the atmosphere. Numerous passive RT formulations applicable to terrain features have appeared as well (e.g. Kong et al, 1979; Shin and Kong, 1982 and 1989; Tsang, 1991).

## II.2 SCATTERING FROM SURFACES AND TRANSITIONS

At least until the present, our options in connection with surface scattering computation are relatively limited in the sense that only mild to moderate roughness of one kind or another can usually be treated. The by now "classical" approaches are based on the assumption that physical optics (PO) or small perturbation method (SPM) approximations are adequate. Lucid formulations of these methods are presented in a variety of texts (Ishimaru, 1978; Tsang et al, 1985; Kong, 1986) and together with their recent developments are extensively reviewed (e.g. Ulaby et al, 1982; Fung et al, 1990). Multi-scale roughness formulations have been developed, combining disparate ranges over which the approximate theories hold. Physical and numerical surfaces have been constructed and scattering behavior measured or obtained numerically to investigate the applicable ranges of validity (e.g. Chen and Fung, 1988; Fung et al, 1990; Lou et al, 1991). Ishimaru et al (1991) perform numerical, analytical, and experimental studies of very rough surfaces relative to the "classical" constraints. Their MMW experiments and numerical analyses of surfaces with known statistics illuminate enhanced backscattering from rough surfaces. While significant questions remain as to the detailed limitations of these theories, a general consensus emerges. This is reflected in the above references, in those discussed below, and is summarized succinctly by figures published in various locations by Ishimaru and coworkers (e.g. Ishimaru and Chen, 1990). Generally speaking, it is difficult to perform reliable calculations for rms surface height fluctuations approaching or greater than one wavelength, or for rms slopes approaching

unity. Perturbation methods are preferable at small correlation lengths, with PO based methods more successful for larger rms heights. The strength and appeal of these methods lies in their ability to provide information on expected coherent and incoherent scattered field properties based on (statistical) spectral characteristics of the reflecting surfaces.

The Kirchhoff approximation (KA) constitutes a PO approach in that it uses the tangent plane approximation for surface fields to express sources in the diffraction integrals. This approximation assumes that scattering of the incident field may be approximated locally as if reflection were from a flat surface with slope equal to the tangent to the actual curved surface. Alternatively, it may be stated that PO assumes induced surface currents equal locally to the corresponding geometrical optics plane wave fields. The diffraction integrals are extremely widely used in surface scattering formulation and computation in all the methods discussed here. As 2-D (surface coordinate) equivalents of their Green's function based 3-D WT counterparts, they may be viewed as expressions of Huygen's principle, or simply as the results of various integrations and manipulations of the underlying electromagnetic wave equations. The integrands contain (usually) unknown tangential field or equivalent current values, which serve as sources of the general field to be calculated. Use of the tangent plane KA approximations to obtain these surface sources implies a large radius of curvature on the scattering surface, relative to the incident wavelength. This statement does not supply a very precise criterion for range of validity, and investigations have shown the importance of having a relatively large correlation length, even for rms heights that one might suppose corresponded to mild radii of curvature (Thorsos, 1988). Except perhaps in some deterministic cases, additional assumptions must typically be made (including small slopes and constant Fresnel reflection coefficients) otherwise evaluation of the integrals cannot in general be carried out. With the stationary phase approximation applied in the high frequency limit one obtains the geometrical optics approximation (GO). This implies essentially that only parts of the surface with local specular scatter towards the observer contribute to the integral. The Fresnel coefficients applied within conventional KA formulations have polarimetric content in the sense that they are different for

horizontal and vertical polarizations. However this inclusion of polarization effects is approximate at best, and one should not expect complete and accurate polarimetry based on classical KA formulations. Without the additional of special measures, such formulations also do not conserve energy in general, hence one cannot obtain reciprocal information from them, i.e. the use of active to infer passive behavior.

Over recent years the shortcomings of these approximations in terms of shadowing and multiple reflection have been attacked and higher order versions have been constructed (Ishimaru and Chen, 1990; Chen and Ishimaru, 1990). Successful application of these enhanced KA treatments is seen even at slopes on the order of unity, with rms heights and correlation lengths somewhat greater than one wavelength. Thus these formulations may be capable of addressing the roughest surfaces, without handling the smallest correlation length range. We note as an important advance that energy is conserved in these calculations. At the same time, the introduction of the shadowing and tapering functions is cumbersome and requires further study. For the most part, simulation of two-dimensionally rough surfaces is still to come, awaiting the completion of more tractable numerical treatments of fully vectorial electromagnetic scattering.

In contrast to the PO based approaches, the SPM proceeds by applying a correction factor to the field that would be present on a flat surface located at the mean of the actual surface. This factor is expanded in a perturbation series. Small rms surface heights and slopes are required. Relative at least to the more basic KA formulations, SPM has the advantage of being fully polarimetric in principle, although cumbersome higher order calculations may be required for reasonably accurate and complete polarimetry. Recently the phase perturbation method (PPM) has been introduced as a sophistication of SPM (Winebrenner and Ishimaru, 1985). Exploration of the method by workers at the University of Washington and elsewhere have established a considerably wider range of application of PPM relative to the more traditional SPM formulations (see figure in Ishimaru and Chen, 1990).

Fung et al (1992) have extended earlier work for perfectly conducting surfaces (Fung and Pan, 1987) so that computations for dielectric surfaces

can be carried out in the same manner. The resulting integral equation method reduces to KA and SPM terms at the appropriate limits for both like and cross polarized results. Good results are shown with the new method for rms surface heights on the order of the wavelength and slopes (i.e. correlation length divided by rms height) approaching 0.4.

The unified perturbation method (UPM) has been introduced and tested by Rodriguez, Kim, and coworkers (Rodriguez and Kim, 1992; Rodriguez et al, 1992; Kim et al, 1992). A perturbation expansion is used which converges over a wider domain than SPM, and which converges in the appropriate limits to the KA, SPM, and two-scale results. In the last case, this is accomplished without the introduction of an artificial adjustable parameter for the spectral split. Recent 1-D roughness tests show success in addressing surfaces with rms height approaching one wavelength with rms slopes less than or equal to about 0.8, for both horizontal and vertical polarizations. In addition to the obvious merits of the UPM system on the basis of this reported performance, we pause to take note of a particular application of the method to ocean backscatter simulation. Little or no work has been done on ocean simulation in our frequency range, in any case not with meaningful tests against data. The ocean is attractive for analysis in as much as it is a rare example of relatively pure surface scatter, sea spray and breaking waves notwithstanding. At the same time, there is usually a lack of "ground (water) truth" on which to base analyses. One must simulate both the water conditions and the consequent electromagnetic response as functions of other variables, most notably wind speed. Rodriquez et al (1992) have performed Ku band altimetry oriented simulations of scattering from ocean surface, based on a simplified ocean spectral model driven by wind speed. While there are some discrepancies in results relative to observations or other studies, important agreements are achieved, particularly in connection with EM bias. This bias is caused by two modulating mechanisms, one due to small scale waves and the other a result of tilt due to large waves. The one-dimensional surface roughness bias calculations show proper trends with respect to both frequency and wind speed, based on independent physical observations. Bias increases with wind speed, but ultimately saturates as wind continues to rise. The computed sign of the EM bias is correct relative to observations; the difference in magnitude by a factor of two may be due to use of the

simple 1-D spectrum. UPM codes containing 2-D roughness are nearing completion and may offer more precise agreement. While the wavelength in these simulation is approximately half that at 35 GHz, it is close enough to encourage strong interest from the MMW point of view. Despite the limitations of this combined ocean - electromagnetic study, it deserves to be singled out as a source of simulations of some significance and validity.

While these newer approaches have pushed the bounds of application of surface roughness treatments, it is still difficult or impossible to address a great many realistically rough surfaces with rms roughness heights greater than the incident wavelength and especially with large slopes. These constraints can be severe at MMW frequencies for natural media like soil, gravel and sand, moving water, or tree bark. In practice, most volume scattering models that attempt to combine surface scattering adduce one of the "classical" formulations, such as KA with stationary phase. This can serve to provide an example of (interacting) surface and volume effects, but it rarely approaches the full physical reality to which one would like to apply these models, such as agricultural fields.

In practice, surface and volume scattering effects cannot be separated to the extent that the above discussion might suggest. Perhaps more often than not, one encounters physical transitions in the media being sensed that contain elements of both; or that produce a kind of effect which cannot be accounted for by either or both in simple combination. For example, bare tilled or raked soil may be quite rough on the MM scale, with clumps and heterogeneous protrusions containing vertical slopes, large void inclusions, and the like. From one point of view, we confront a distinct (albeit complex) scattering interface between air and sharply contrasting soil media. From another view, one sees a heterogeneous volume of scattering material over a transition zone, beginning with a low density at the highest point of soil protrusion and gradually increasing in density, homogeneity, and continuity with depth. This sort of surface-volume scattering ambiguity problem is most likely to arise for very rough surfaces; such surfaces are not entirely uncommon in practice. Certainly the traditional, mild roughness theories and their most recent improvements will ultimately fail for sufficiently rough transitions. It is also reported that surface scattering

approaches must be modified in the face of dielectric heterogeneity, even when the bounding upper surface is geometrically smooth. Numerical simulations of an imaginably soil-like medium with voids and inclusions near the surface show behavior influenced significantly by the sub-surface character, even in cases in which penetration by the radiation should be slight.

Revelations provided by simulations may serve to indicate the best way at present to investigate medium configurations and effects such as these. Monte Carlo or other structured numerical experiments may guide us towards the best approaches at a more analytical or conceptual level. In any case, we do not yet have good methods for analyzing such cases with any real generality, and do not have good guidelines as to how to proceed.

## II.3 STATISTICAL QUANTITIES AND MONTE CARLO CALCULATIONS

Before passing to the next section, we pause for a some general observations on what we seek in any approach of the sort we are considering, on what sort of quantities are to be employed, and on what the nature of the methods is that allows us to obtain them. Basically, for natural media, *statistical* quantities must be generated regarding the application medium. Most commonly these consist of an rms variation of permittivity for volumes and of surface height for an interface, or the equivalent; plus some measure of the spatial scale and geometry of this variation, most commonly through correlation length. Loosely speaking, the correlation length indicates the general size of a significant permittivity variation or of a discrete scatterer in a volume, or the lateral extent of a contour variation on a surface. As such, correlation lengths may be anisotropic in the sense that different lengths may apply in different directions, as for elongated brine pockets in saline ice or for narrow striations in a surface. The fact that directional information can reside in the correlation length underscores the significance of this quantity for polarimetric modeling. While some polarimetric information can be dealt with in models without directionally different correlation lengths, we should not expect fully polarimetric results from such vehicles when, in fact, most media are to some degree anisotropic. We also note that

the correlation length does not entirely define the correlation function itself, given that the former is typically only defined as the distance over which the function decays by 1/e. The entire function itself will depend on the case considered; a Gaussian function is often used. One should note that the indication of a "Gaussian surface" usually means that the correlation function or, equivalently, the power spectrum of a surface has the form of a negative exponential of distance squared. This does not mean that the variation of surface height is assumed to follow a Gaussian *probability* distribution, though that is also often the case.

The appearance of statistical quantities in both remote sensing data and its modeling implies some particular kind of averaging procedure. In physical measurements this is performed, in effect, by the sensor. One footprint presumably spans many patches or subregions, in each of which a sufficient sample is present for statistical quantities to apply meaningfully. Thus integration is performed over each subregion patch and the ensemble of subregions is summed as well. Quite significant questions remain as to the correspondence between the kind of averaging implied in the theoretical bases of our models and that performed by any likely or conceivable sensor. Among other things, received data is likely to contain effects due to the variability of medium properties at a number of different scales, e.g. at both the subregion scale and at the scale of the ensemble of subregions. In model formulations, the averaging process is typically carried out analytically, at a single scale, in the process of constructing governing relations. This means that the formulations are ultimately stated in terms of the statistical quantities themselves, such as expected or coherent field and the diffuse incoherent field or average power. These theoretical average quantities presuppose a certain kind of averaging, typically, averaging over an ensemble of surfaces, conceptually subjected to the same illumination regime and developed as realizations of the same statistical process. In this context, the correlation function, for example, means the correlation value of quantities (e.g. surface heights at a given separation) *averaged over the ensemble of surfaces*, not averaged spatially over a single domain. The latter sense of averaging, however, is often the one employed in practice when a limited domain is characterized experimentally to provide model input. While

the two averaging processes bear some relation, questions remain in any given application as to the correspondences of the quantities obtained.

Lastly we mention Monte Carlo techniques as an approach to calculation of responses of random media. Such techniques have received a great deal of attention recently as computing power has increased. The attraction of the non-Monte Carlo techniques resides in their ability to proceed directly in relating statistical and spectral features of the modeled medium to the statistical properties of the received field or power. In such approaches, ensemble averaging is carried out analytically in the course of the formulation procedures; this is a result of the analytical simplicity of the expressions used and the introduction of limiting simplifications. By contrast, in Monte Carlo simulation one calculates the response of specific, geometrically defined (deterministic) medium samples, perhaps analogous to the "patches" mentioned above. This is typically done numerically. Each of the samples is constructed to be an individual realization of the hypothesized underlying statistical formation process. Once solutions have been obtained for a sizable number of such instances, one adds them together to obtain effectively an ensemble average. Thus by "brute force" one mimics the supposed process by which a sensor might accomplish its averaging integration, and one also accomplishes a faithful rendering of the kind of averaging assumed in the more approximate analytical models.

Monte Carlo techniques have the attraction that one can avoid many of the limiting assumptions needed to obtain results in the more analytical approaches. Also, because the details of the modeled media are known, there are no unknown tunable parameters, the estimation of which can render data-matching exercises suspect. In surface scattering, going beyond the constraints of analytical approaches on scale of roughness or severity of slopes means that one can work with truly realistic surface profiles (at least in 1-D). This is accomplished, however, at impressive computational cost; two dimensionally rough surfaces are rarely attempted, though we expect progress here in the near future. Truly Monte Carlo treatment of volume scattering in the manner done for surfaces is currently out of the question. The sheer detail required to describe the internal geometry of a *realistic*

volume of environmental material is insurmountable; the computational requirements will also be invincible in the near future, for solution of electromagnetic equations over a truly life-like variation of internal medium geometry. Monte Carlo volume scattering treatments in a certain limited sense have been carried out in the constuction and analysis of collections of very simple shapes. For example Ding et al (1992) have used Monte Carlo procedures in achieving arrangements of spheres to determine the statistical pair distribution functions needed for their dense media volume scattering calculations. Tsang et al (1992b) have solved Maxwell's equations rigorously over similar dense media, for cases with as many as 4000 spheres, presumably with volume fraction limits imposed by the convergence of the iterative solution procedure. Good solutions were obtained at densities of 25% by volume. Alternatively, Chuah and Tan (1992a, b, c) have used Monte Carlo procedures for the calculation of a cascade of idealized contributing scattering events in vegetation. This statistical treatment of the contributing scattering events is fundamentally different from a rigorous deterministic analysis of events on a precisely realistic geometry for later ensemble averaging, i.e. for Monte Carlo treatment as meant here; see discussion below. In addition, because they proceed on the basis of a photon transport equation and not Maxwell's equation, coherent interactions as needed for dense media are absent. This may suffice for some vegetation applications. Tsang and coworkers are also evidently applying Monte Carlo WT analyses to obtain coherent and incoherent effects for vegetation which, though not dense, is clustered.

In summary, we may not look for volume scattering progress in the near future from the ensemble averaging of numerical solutions of Maxwell's equations over truly realistic geometries in the same manner as is occuring for surfaces. Beyond this we note that pushing roughness limits using numerical solutions brings dangers with its opportunities. Even in the more analytical approaches, more information on the distribution of the medium is generally required than just rms of variation and correlation length. The specific character of the overall correlation function is needed or assumed; in volume scattering one needs density information; and other higher order spectral or geometrical information may be required for complete analysis. This is particularly so when the limits of the approximate theories are surpassed. It

has been noted that a number of different models may produce reasonable agreement with observations while using contrasting versions of the underlying physics, even when the input data have been constrained by ground truth measurements (Carsey, 1993). Among other things, this serves to re-emphasize the fact that rms variation and correlation length do not uniquely define the system. For more extreme yet realistic media, we will have to recognize and implement additional parameters that catch the particular character of the variability, beyond what is incorporated in the traditional quantities. This makes sense, and is even desirable: it says that we need to focus on the identification of new, specific, distinguishing medium characteristics that can be linked to some distinguishing statistical character in the received data. Only by doing this will we recognize realistically distinct media in our sensed data. While overall this is likely to mean that we must consider additional parameters, such as higher statistical moments, in some instances it may mean that we discard altogether one or more of the traditionally important medium quantities. One might even say that we require new physically based, probably case dependent parameters and signal characterization specifically to simplify our task to the point of tractability.

# III. APPLICATIONS

The following is suggested as a general scheme of media and physical features for which models are sought. In each case both active and passive polarimetric systems are ultimately desired.

Cultural features

- buildings and transportation constructions, urban/suburban environments, edges or linear structures such as roads and wires

Atmospheric applications

- active propagation and emission horizontally and up/down through profiles of clear air, turbulence, dust, clouds, precipitation

Vegetation

- low: grass, fields, agricultural plantings, shrubs, mostly single layer with diminished importance of branches, greater importance of leaves, blades, stalks

- tree canopy: usually but not always two layer, continuous/ intermittent crown with branches and seasonal or evergreen leaves/needles, lower layer of trunks, horizontal and non-horizontal propagation; as for low vegetation, possible significance of underlying ground/water surface

Snow and ice

- snow: shallow/deep, uniform/layered, wet/dry, smooth/rough

- ice: fresh/saltwater, smooth/jumbled, first year/multi-year

Exposed terrain and water bodies

- rock: rock strewn terrains, or more monolithic formations which may be mooth except at MM scale, or may be steep, jagged outcroppings

- soil: wet/dry, rough/smoothly undulating, multi-scale roughness

- water: smooth/rough, moving/still, expansive/narrow

- sub-pixel patches: mud puddles, ice patches, thaw/wet patches in snow....

This list is something of a litany of objectives, as context. Below is a summary of what has been done on the way towards addressing this list.

## III.1 CULTURAL FEATURES

Clearly one can attempt to analyze specific constructed elements such as wires, stairs, or windows. However here we seek more generic capabilities applicable in relatively indiscrimminate remote sensing of a large scale environment. Relatively little has been done in the way of modeling lower frequency microwave sensing of large scale constructed or cultivated environments, and even less is available in the public domain at MMW frequencies. A few measurements have been reported (e.g. Violette et al, 1988) but without substantial attempts at modeling. Beyond the obvious (such as considering buildings or curbs as corner reflectors) we draw no inferences here for modeling purposes. We note that the constructed or controlled nature of cultural features offers greater regularity to the analyst on the one hand: swimming pools, walkways, and even lawns have relatively distinct edges. On the other, the sheer variety of features and their distinctive forms provides too great a welter to permit much generalization. For well defined structures and their environments it may sometimes be possible to use various programs in the suite available from the Georgia Tech Research Institute (Peifer et al, 1988; Faust et al, 1989; Davis et al, 1992). This graphically facilitated package offers capabilities for defining structure geometry and then calculating returns in terms of combined PO responses of an assemblage of simple shapes (scattering centers). In less deterministic situations we may consider the possible presence of highly distinct structures at the sub-pixel level, that is, a terrain category of "patches," each of which may be relatively easily to model in itself but which must somehow be integrated statistically into an image effect. Rational, or at least rationalized schemes exist for constructing "fading" (speckle) in images from this sort of process. Such schemes can be based on reasonable or at least specific physical assumptions and procedures (e.g. Ulaby et al, 1982 and 1986; Yueh et al, 1991). While they come into play during during the final steps in the scene generation sequence, we consider that they fall within the fringes of the domain of

modeling that we are pursuing here. For this reason, no specific review of approaches and programs and no recommendations in this area are included in this report.

Some expansive cultural features such as lawns, bare tilled soil, or crop fields may be attacked under other headings below.

## III.2 ATMOSPHERE

Many of the radiative transfer approaches listed below can in principle be applied to atmospheric dust and precipitation. Models have been developed by Ishimaru and coworkers that are in principle applicable to rain or ice precipitation (Ishimaru and Cheung, 1980; Ishimaru et al, 1984a and b), and others are directed at turbulence effects (Honig et al,1977; Ishimaru and Painter, 1980). McMillan et al (1982) review applications of theory to measurement for MMW propagation. They conclude that while in most cases agreement is "plausible," data have been inadequate to determine the extent to which this is fortuitous. Weinman (1989) applies a Rayleigh-Gans model of MMW scattering from falling snow, with flakes considered to be a polydispersion of equivalent randomly oriented circular disks. Disk dielectric constants are obtained from the Bruggemann mixing rule with estimated ice fractions in the equivalent flakes. Theoretical comparisons with measurements are good at 35 and 94 GHz, although the author emphasizes the need for access to more comprehensive data.

In general, efforts to model realistically complex metereological events in a natural setting are hampered by our inability to characterize the medium (lack of "air truth," as it were). Despite these difficulties we single out three sources of simulation that have seen some notable application: the work by Al Gasiewski at GA Tech, the RADTRAN program, and the MPM program.

The most comprehensive and authoritative data measurement and modeling basis for atmospheric attentuation/delay is provided by the MPM model of

Liebe and colleagues (Liebe, 1989; Manabe et al, 1989; Liebe et al, 1989; Liebe, 1992). The MPM model is the generally acknowledged standard for predicting profiles of complex refractivity of the neutral atmosphere from 1 to 1000 GHz with contributions from dry air, water vapor, suspended water droplets, and rain. For clear air, the local line base (44 $O_2$ plus 30 $H_2O$ lines) is complemented by an empirical water-vapor continuum. On the whole, the basis for the relationships in the MPM program and its testing lend it very high credibility. Possible shortcoming reside in missing trace gas spectra and the empirical water-vapor continuum. The physical origin of the latter is basically understood, however its empirical construction could possibly lead to errors in predictions for some atmospheric window ranges. Even with these caveats, we note that the precision offered by this model probably surpasses that provided by any other model considered here by quite a bit. Perhaps the most approximate component is the treatment of rain effects. No attempt is made to engage in elaborate calculations for individual drops, such as would require drop shape and size distributions, variable permittivity of the water, etc; similarly, no complicated RT type computations are employed with an assumed or empirical phase matrix. Rather the refractivity of the rain is expressed simply by a formula, with constituent terms and factors developed from a least squares fit to Mie calculations based on a Marshall-Palmer drop size distribution. Overall, this gratifyingly simple code is easily implemented and can feed into the more complex modeling vehicles discussed below.

Gasiewski has produced a program for calculating brightness temperature and associated statistics for planar stratified scattering atmospheres over specularly reflecting surfaces for the 1 - 1000 GHz frequency range. Emphasis is more on the handling of complex precipitation events. The atmospheric portion of the model is described by Gasiewski and Staelin (1990); a wealth of details on the formulation, sensitivity and exploratory runs, and comparison to measurements is also provided by Gasiewski (1993). In general, this RT model assumes Rayleigh scattering or Mie scattering from spheres. Given the expected sparse distribution of scatterers, models simpler than the Mie formulation are typically used to determine the form of the phase matrix, which is less influential than the other parameters. Both

iterative and quadrature solutions are pursued, and both mono- and poly-dispersed hydrometeor scattering and extinction are considered. Isotropic, Sobelev (two-term), Rayleigh, Henyey-Greenstein, and two-stream phase function formulations are offered. Ground surface reflectivity is considered to be a minor influence in the applications considered, and is typically assumed to be a convenient fixed value, e.g. 5%. Downward looking brightness temperatures were calculated for flight paths over a relatively complex summertime convective cell couplet, with concomitant data from weather radar reflectivity used to determine hydrometeor size distribution and phase profiles (Gasiewski, 1993). Agreement between observed and computed values is impressive. It appears that the model would benefit from the inclusion of some polarimetric effects under certain precipitation conditions. This may be accomplished to some degree through inclusion of more asymmetric particle geometry and scattering; more general polarimetric ground surface reflectivity is also planned.

The computational vehicle designated as RADTRAN has been developed from work originally done at the Air Force Geophysical Laboratory to model atmospheric transmission and emission in the 30 - 300 GHz range (Falcone et al, 1979, 1982). The package is oriented towards passive measurements and contains six each of clear atmosphere, cloud, rain models as well as eight humidity models in an attempt to cover a worldwide variety of conditions. The original RT formulation has been upgraded more recently by Isaacs and coworkers at Atmospheric and Environmental Research, Inc. (Isaacs et al, 1988, 1989a, b, and c). The enhancements allow RT simulation of polarized multiple scattering for cases involving various kinds of precipitation and surface emissivities. Jin and Isaacs (1987) show exploratory computations of hypothetical cases with a polarimetric formulation in which the required scattering functions are based on Mie scattering. It appears that polarimetric effects enter essentially through the calculated terrestrial surface emissivities. In any case, it is not clear that this particular formulation has been built into the RADTRAN package. Other papers referenced above indicate that the package enhancements avoid an on line computation of precise Mie scattering for each specific particle size, phase, temperature, and frequency combination. Rather, interpolations are

performed on parameterized results of Mie scattering calculations for representative particle size distribution functions under different conditions. The ultimate results appear to be accurate when compared to calculations based on full fledged Mie scattering computations (Isaacs et al, 1988).

The enhanced RADTRAN is now designed to handle emission from a variety of surfaces of user specified type. The surface or surface layer models used are quite simplistic: Calm ocean is modeled as a dielectric slab; rough ocean, sea ice, and wet and dry snow are modeled using discrete random scatterer inclusions and WT; vegetation, wet and dry soil are treated using RT and a continuous random medium model. These surface models enter significantly into calculations of polarized brightness temperatures that compare reasonably with SSM/I data over selected areas (Isaacs et al, 1989b), with further comparisons needed over snow, sea ice, and soil. It seems that essentially all of the specifically polarimetric content in the data comparisons enters through these surface factors, rather than through directional structure and scattering properties of precipitation particles. We note that the extremely approximate nature of these surface models makes it unlikely that they would stand up to the kind of testing applied elsewhere to more sophisticated models with mixed results at best. Most features of the original (1979) version of RADTRAN test well against laboratory data; parts of the package related to heavy precipitation and the most recent enhancements have seen only rather sketchy validation heretofore. Most recently (Pickle et al, 1993) the program was used to help quantify the uncertainty in DMSP SSMT/T-2 water vapor sounder brightness temperature measurements. Under precipitation-free conditions with clear or partly cloudy skies over land and sea, collocated radiosonde temperature and moisture profiles were used as input; outgoing radiance was calculated. In the context of both satellite and NASA ER-2 underflight radiometer data, the model estimated sensitivities of the brightness temperature to variations of moisture content.

Overall, the RADTRAN package has the substantial advantage that it is documented, facilitated, disseminated, and supported. It includes many accepted, state-of-the-art formulation features for atmospheric modeling.

Gasiewksi's model, which shows comparable care in formulation, currently eschews polarimetric effects and treats the terrestrial surface extremely simply. It shows good results against data for a complex precipitation event, with simulations backed by independent "air truth."

## III.3 VEGETATION

Perhaps the simplest MMW canopy model is the scalar RT formulation of Schwering et al (1988), utilizing a parameter extraction and solution system reported separately (Johnson and Schwering, 1985; Schwering and Johnson, 1986). Only horizontal propagation is considered, so that no layer boundaries are encountered. Three elevations at different parts of a tree canopy are treated, at seasons with and without leaves present. This model has both the attraction and the limitation that it was developed closely in tandem with relevant data acquisition and processing. One can see immediately what the model does in application to data from a two layer canopy of "real" vegetation (a "regularly planted, well groomed stand" of pecan trees), but it is not clear how widely it might be generalized. The formulation goes directly to the form of an assummed phase function, which is just the scalar function

$$p(\gamma) = \alpha(2/\Delta\gamma)^2 \exp[-(\gamma/\Delta\gamma)^2] + (1-\alpha)$$

where $\gamma$ is the angle between the incident and scattered directions of energy propagation, $\Delta\gamma$ is the beamwidth of the forward lobe and $\alpha$ is the ratio of the forward scattered power to the total scattered power. Thus one assumes a strong forward lobe and an isotropic background. In addition to constituents of the scalar extinction coefficient, only the two parameters above are used, and these must be estimated from experience or with reference to some representative data. Still, with reasonable values of the parameters ones sees good qualitative agreement with the measured data.

Different behaviors are notable at different levels in the canopy, with strong coherent forward lobe at small optical depths. This component broadens and decays rapidly with depth. The very rapid decay at shallow depths is due both to absorption and scattering, while beyond shallow depths the attenuation is due almost entirely to absorption alone as scattering only reproduces the incoherent component. There is a fairly sharp transition to the much more slowly decaying, isotropic intensity which ultimately predominates.

We dwell on this model in part because of its attractive simplicity. It shows fidelity to the general character of the measured data without elaborate, costly, and perhaps unrealistic attempts to define scattering and extinction matrices, without significant CPU time, and without consideration of coherent effects. While much more sophisticated models exist, one can question the cost/benefit of pursuing them in light of inevitable uncertainties.

Test environments like that used by Schwering et al are desirable in that they are relatively uniform and controlled, but one may be wary of artificial effects due to their constructed regularity. Tavakoli et al (1991) perform an exercise similar to that of Schwering et al, measuring and modeling propagation through a horizontal, planted vegetation canopy. The plants constitute only a single layer (corn), but as above the arrangement of the plants is quite orderly relative to untrammeled nature. An attempt is made to treat the medium as random within rows, with some deterministic interaction between rows. Thus it is a "semi-deterministic" field approach featuring notable coherent phenomena, agreeing impressively with the observed data. Perhaps the point to be made here, however, is that this latter study was done at L band, such that individual leaves are much smaller than a wavelength and stalks might be considered smooth. In the azimuthal scanning data presented by Schwering et al (1988), one sees significant scintillation due to coherent effects not accounted for in the model. However the variations of signal strength are extremely rapid; statistically the profiles are smooth or nearly flat, and clearly the correlation length of millimeter waves in a forest is extremely short. Also, the field rapidly becomes thoroughly depolarized. Effects of the sort

pointed out by Tavakoli et al were swallowed up in the MMW regime by the strong scattering of the vegetation elements, rapidly producing a predominately incoherent field. Even structures viewed grossly as linear and distinctly oriented (e.g. tree trunks) may easily have bark that is so rough on the MM scale that the linearity and orientation of the trunks/branches is largely irrelevant. Some of the models admirably constructed from detailed analysis of idealized forest elements may apply in UHF and microwave regions where elements are often on the order of the incident wavelength or smaller. In those models, Shwering et al assert, only the forward scattered incoherent component is likely to be important, together with the coherent component. Schwering et al emphasize their conviction that at MMW frequencies the incoherent, multiscattered component is likely to be predominant and must be given corresponding importance in any modeling.

Ulaby et al (1988) pursue further the course set by Schwering et al (1988) by developing an RT model at 35 GHz in conjunction with measurements. Noting the geometrical diversity of the target trees at MMW and expecting very weak polarization dependence, they adopt the general form of the scattering function in the equation above but with the forward lobe represented as $2(1 + \beta_s^{-2}) \exp[-|\gamma|/\beta_s]$, in which $\beta_s$ is a measure of the effective beam width of the forward lobe. The constituent parameters in this expression and extinction coefficients are derived from measurements on individual trees of a couple of types. While Schwering and Johnson present a solution formulation that accounts for all orders of multiple scattering, and Schwering et al (1988) emphasize the advisibility of accounting for extensive multiple scattering, Ulaby et al limit the formulation to first order results. Calculated attentuation agrees well with observation.

Ulaby and coworkers pursue this line of investigation further by polarimetric measurement and modeling of MMW scattering from a tree canopy (Ulaby et al, 1990). Essential focus is on the crown. Noting that "at millimeter wavelengths the penetration of foliage rarely exceeds 1 m" they treat both the upper and lower canopy boundaries as diffuse and non-reflecting. Despite very substantial small scale morphological differences

between the tree types investigated (ficus versus arbor vitae), the like-polarized (hh and vv) scattering patterns were approximately the same for each tree type; and those for the contrasting tree types also resembled one another. The same held true for the cross-polarized patterns. Ulaby and coworkers have pursued specific modeling and measurement of leaf scattering patterns, with increasing morphological and constitutional complexity for the leaves and with increasing incident frequency (Senior et al, 1987; Sarabandi et al, 1988; Sarabandi et al, 1990). Nevertheless Ulaby et al (1990) take the view that 1) truly realistic MMW phase functions for the variety of vegetation elements cannot currently be determined, 2) if they could be determined, realistically complex phase functions would be computationally intractable, and 3) the observations above for different tree types warrant the use of a simple assumed scattering pattern and consequent phase function in any case. Phase functions similar to the two displayed above are obtained from data for individual samples of the vegetation. Iterative first and second order and "exact" numerical solutions of the vector RT equations are obtained. While it is unclear why the second order solutions should apply in an evidently inappropriate albedo range, computed backscatter solutions compare favorably to measured data.

While the result does not surpass the models above in rigor, Borel and McIntosh (1990) construct a simple model for expressing backscatter from deciduous trees including leaf orientation distributions. This can be seen as a step towards generality and rational basis in as much as it includes a basis for distinguishing the responses of different trees in terms of the physical characteristics of constituents. Measurements at 35 and 94 GHz of individual leaves was used to justify the use of an average leaf radar cross section when computing the normalized radar cross section (NRCS). A simple system is used to superpose the individual leaf contributions, using orientation distribution and incidence (viewing) angle. Orientation dependence in the results is used to justify similar analysis of data from a variety of tree forms at 215 GHz. The modeling is quite approximate in that fine scale leaf roughness, polarization, and shadowing effects are neglected, among other things. However a noteworthy result of the combined analysis and data is the observation that one is able to distinguish returns from different (planophil, erectophil) morphology classes despite substantial differences

between individual members within each class, based on characteristic leaf orientation. This serves as a refinement of the above mentioned work by Ulaby and colleagues, in that McIntosh's group show differences in polarimetric returns distinctly as a function of tree type, or at least class of tree type.

These observations are intended to highlight the particular nature of MMW scattering from environmental features; to serve as a warning against the facile extension of lower frequency modeling approaches to MMW; and to suggest restraint on attempts to build sophisticated model structures based on gross features. Having said this we proceed nevertheless, adhering to the faith that more aggressive analysis will eventually provide useful tools beyond the otherwise extremely simplistic devices at our disposal heretofore.

Lang and coworkers at George Washington University (GWU) have developed primarily WT vegetation models for some time, attempting to include more specific analytical characterization of the canopy scattering elements. In early work leaves are modeled as circular dielectric disks (Lang, 1981), with the addition of a flat lossy ground surface and orientation statistics for lossy leaves (Lang and Sidhu, 1983). The Foldy approximation was used, implying sparse media, and leaf sizes were assumed to be smaller than the incident wavelength. Some attempt has been made to include higher frequency effects in theory for individual leaf scattering behavior (LeVine et al, 1983). Some recent RT work by Lang and colleagues approaches small wavelength limits (Lang and Yazici, 1989). The culmination of the line of work by the GWU team in terms of an available model is WT based, allowing for different classes of scatterers in two layers, each with a specific orientation distribution. Underlying surface roughness is treated by KA theory. Polarimetric backscatter coefficients are computed using the distorted Born approximation. The formulation implies contributions from direct volume scattering, a direct-reflected or double bounce ground-vegetation term, a bottom reflection contribution and a surface scatter term. Flat or curved discs with circular or elliptical shapes may be selected, as well as linear (cylindrical) members. For the most part the programs are oriented towards P, L, and C band; simulations have used ground

truth input and been compared where possible with measured backscatter for various canopy scales including grass, soybeans, corn, and forest (e.g. Saatchi et al, 1991; Chauhan et al, 1991). Formulations for thicker disks, needle arrays, and resonant size cylinders are being included so the system can be used at MMW wavelengths, with simulations performed at 10 - 50 GHz. Experimental validation at these frequencies is reported to be underway.

Fung and coworkers have also attempted to build specific leaf and branch character into vegetation models for frequencies higher than those considered in previous models. Using the Rayleigh-Gans approximation, a first order RT formulation is presented that should be valid for leaf dimensions up to the size of the incident wavelength (Karam and Fung, 1989). Size variations are included through elliptic disk leaves and needles for conifers. On the basis of simulations it is suggested that both like and cross polarizations may be needed to distinguish leaf type effects on scattering behavior. As frequency increases, near field effects enter increasingly in leaf to leaf field interactions. Fung et al (1987) allow leaves to be in the Fresnel zone of one another for both disc and needle shaped leaves. VV and VH measurements are matched to calculated X band scatter for soybean plants. Liu and Fung (1988) use an empirical parameterization of vegetation material with a rough underlying ground surface to perform polarimetric scattering computations for $k \cdot a$ values approaching 4, where $a$ is a characteristic leaf dimension. Comparisons of computations with data are good. A first order RT formulation for randomly oriented dielectric cylinders is used by Karam and Fung (1988) to link surface scattering with that from a defoliated vegetative volume. While comparisons to data are best for lower $k \cdot (a$ = cylinder radius) values, favorable comparisons are seen as high as $k \cdot a = 2$. While MMW frequencies strain these $k \cdot a$ limits, leaf sizes and branch radii up to some significant fraction of a centimeter could possibly be accommodated at 35 GHz.

Tsang and coworkers at UW, MIT, and GE have developed vector RT models that may be applicable to vegetation over rough surfaced soil (Tsang et al, 1990; Tsang, 1991; Tsang and Ding, 1991; Tsang et al, 1992). First order, second order, and full multiple scattering solutions are obtained. Extinction and phase matrices are calculated in such a way that energy is

conserved and reciprocity preserved. Application to measured data is awaited.

In an interesting new approach pursued separately by investigators at MIT and GWU, models are designed to include effects of vegetation architecture. That is, one notes that the needles on an evergreen, for example, are distributed with a randomness that is structured by the basic tree morphology; needles cluster with predisposed alignment along twigs and larger branch elements. Thus the needles may effectively form a random distribution of arrays. Drawing on such observations of underlying architecture also allows incorporation of the multi-scale nature of vegetation systems. Yueh et al (1992) employ two scale branching models with idealized independent scattering behavior of individual elements. Calculated responses for simple structures as a function of frequency and incidence angle show an importance of coherent or phase relations between constituent elements. In application including ground surface effects and a hole correction pair distribution function, good agreement is obtained in comparisons with polarimetric C-band data from soybean fields. While greater small scale coherence effects might be anticipated at frequencies below C-band, it remains to be seen whether the approach produces significant revelations in the higher frequency domain we are interested in. Lang and Kavaklioglu (1991) pursue a related modeling exercise in which they contrast the behavior of randomly oriented elementary needles with that of randomly oriented arrays of such needles. It is assumed that the radius of each cylindrical needle is small compared to the wavelength, which is a reasonable assumption at 35 GHz, if not at 94 GHz. While comparisons to data are not indicated, the modeling evidently showed differences in response between the random needles and random arrays of needles when the wavelength was comparable to the array size. We cannot yet say that the concepts used in these studies has been shown to be of great relevance for MMW simulation. However these first results as well as the appealing rationale of the basic concepts suggest strongly that this is an area to watch.

We close this section with a brief mention of Monte Carlo modeling. Chuah and Tan (1992a) have proposed a model in this connection for backscatter from forest stands. Their approach is "Monte Carlo" in that individual contributing scattering events within the canopy are treated probabilistically and then looked at in their intensity sum. As noted above, this and any other such treatment based on a cascade of statistical events differs fundamentally from the Monte Carlo treatments of surface scattering that have been appearing recently. In the surface scattering case investigators calculate the scattering deterministically from an entire, specifically described, generally realistic geometry. This procedure is repeated many times for different example surfaces and the ensemble of results is summed coherently. In Chuah and Tan's model, the top layer consists of randomly oriented oriented leaves and branches, the next layer is a random distribution of trunks, and a randomly rough soil surface forms the bottom boundary. The medium model differs from that of Karam and Fung (1988) in that Chuah and Tan assume a multi-layer model with a mixture of different classes of scatterers in the top layer. Leaves are modeled as randomly oriented dielectric circular disks or small needles; branches and trunks scatter as infinite cylinders, and the ground is treated using a GO type limit to the KA. The primary distinguishing feature of the approach here is the use of a Monte Carlo method to track photon transport through multiple scattering interactions in the media. Characterization of the interactions at each collision are used to build up an overall transport picture in terms of intensity, not field value as for a WT approach. Using parameters considered to be justified by ground truth, the authors produce calculated backscatter from trees that compares well with measurements at S and X bands. A closely related approach is applied to the computation of emission (Chuah and Tan, 1992b and c). Given its fundamental basis, we assume that the overall approach of Chuah and Tan should produce results equivalent to an RT approach. For this reason, together with the uncertain availability of code and support, we do not pursue the approach further here. However we also note it distinctly as meriting continued attention as an innovative approach that may eventually produce physical results or computational facilitation not obtainable otherwise.

## III.4 SNOW AND ICE

Hallikainen et al (1987) use a simplified strong fluctuation theory following Ishimaru (1978) to model the extinction behavior of snow in the 18 - 90 GHz range. Eighteen types of snow were considered from newly fallen to refrozen. Agreement between computed and observed values is good if the single free parameter of grain size is tuned to a value somewhat less than the observed.

Others at the University of Michigan constructed and tested an RT model for scattering from snow (Kuga et al, 1991; Ulaby et al, 1991). MMW scale scattering from assumed spherical ice particles is treated by Mie scattering expressions to obtain the phase function; non-uniform liquid/ice contact to be expected in small inclusions is modeled by assuming an equivalent "wet air" background medium; the density of the medium is dealt with by the QCA in manner less complete than that of Wen et al (1990); and the equations are solved using the discrete ordinate technique with Fourier decomposition of azimuthal components. The effect of upper snow surface roughness is accounted for in an extremely simple KA stationary phase approximation. The surface formulation has no influence on the intensity field transmitted into the snow, and copolar volume contributions are added incoherently to the direct backscatter from the surface. With the addition of a hybrid first-order numerical solution in the second paper to address the refrozen case, overall good agreement is shown between experimental observations and theoretical calculations.

Narayanan and McIntosh (1990) study high frequency polarimetric backscatter from multilayered snow. Reportedly their model is currently being improved and treats multilayered snow in terms of a cascade of scattering from a number of homogeneous layers with distinct boundaries. The approach utilizes inputs from ground truth measurements, which in their entirety have included surface roughness, moisture content, density, hardness, particle size, and grain type. Total backscattered power is the incoherent sum of surface scatter at the interfaces and a very simply computed volume scatter. An effort is made to include bistatic scattering effects and shadowing on the rough surface. Multiple scattering between layers and ice particles is

ignored. Transmission between layers is considered to be simple Fresnel transmission of fields as for incidence on a solid slab. Slab dielectric constants are obtained from the Polder - van Santen mixing formula for ice spheres and water; volume scattering is computed as the simple summation of Mie scattering from individual grains with a Rayleigh distribution of diameters. Weak surface scattering is computed using the stationary phase KA approximation. Reported copolar NRCS values computed from the model compare favorably with measurements. Further testing is underway.

Fung and Eom (1985) investigate scattering and emission behavior of snow. The medium is modeled as a densely packed matrix of ice spheres; distance dependent terms are kept in the development of expressions for particle scattering as input to the phase matrix. Limitation of the formulation to far field inter-particle interaction resulted in under estimation of computed backscatter and over estimation of brightness temperatures. Computations with near (intermediate) field effects between particles produce superior agreement to backscatter data shown for about 8 GHz. This may generalize to higher frequencies. At the same time one notes that near field effects were entailed here only by virtue of particle proximity, not particle size.

Substantial ground breaking work on volume scattering has come from researchers working at MIT. Using an RT approach, Shin and Kong (1989) calculate bistatic scattering coefficients for a two layer random medium using all four Stokes parameters. The numerical approach provides valid solutions for both small and large albedos; azimuthal Fourier decomposition is used, with Gaussian quadrature and eigenanalysis. Combined volume and rough surface scattering effects are included by modification of the boundary conditions. KA-GO surface conditions are assumed. While measured data are not treated, illustrative computer runs show dominance of rough surface effects for incidence near nadir with volume scattering predominant for large angles. Applications to media and frequencies of interest here are limited by, among other things, the assumption of small permittivity variations.

WT formulations are pursued for volume scattering from random spheroidal and ellipsoidal scatterers, multiple species of scatterer, and for media with size and shape distribution of scattering elements by Nghiem (Nghiem et al, 1990; Nghiem, 1991). At 9 GHz, calculations for sea ice with assumed random ellipsoidal brine inclusions agree well with measurements when a mild surface roughness is treated by the KA and added incoherently. The results show that scattering from brine inclusions is dominant at large incidence angles while the contribution from the rough surface is ascendent at small incidence angles for copolar returns. The first order approximation under the distorted Born approximation appears to give good results for cross-pol backscatter. Further simulations of 4.8 GHz data measured from other samples of saline ice are shown using a model with size and shape distributions for the included air and brine pockets. While there is considerable scatter in the data, simulated and observed trends compare favorably. Questions remain about the applicability of this suite of models to similar media at MMW frequencies.

Researchers at the University of Washington (UW) and collaborators have developed a number of models that may be applicable to snow and ice. Concentration has been on dense nontenuous media and size distribution effects (Tsang and Ishimaru, 1987; Ding and Tsang, 1989 and 1991; Wen et al, 1990; Tsang and Kong, 1992). Beginning with WT concepts, correlated scattering is incorporated via the QCA and QCA-CP for the first moment of the field and and the correlated ladder approximation for the second moment, such that an intensity operator may be obtained that conserves energy. A dense medium RT formulation has also been developed from these approximations to study dense medium multiple scattering effects. A size distribution is employed for constituent particles with pair distribution functions calculated under the Percus-Yevick approximations. Mie scattering is employed at the particle scale; near, intermediate, and far field particle interactions are taken into account such that coherent effects are expressed in the near and intermediate field ranges. Many interesting features emerge from the numerical simulations, such as less scattering from a dense correlated medium than from an equivalent independent scattering medium; much greater scattering from a medium with distribution of particle

sizes compared to a monodispersed mixture of the same average radius; importance of multiple scattering, also illustrated in good agreement between computed and measured extinction coefficients for dry snow (Tsang and Kong, 1992). Illustrative computations of propagation/ attenuation for spherical snow particles uniformly coated with water layers show strong absorption; simulated scattering behavior bears a greater resemblance to that based on independent scattering when the medium has a broad rather than a a narrow size distribution (Ding and Tsang, 1991). This last model awaits validation. We note that in reality water is not uniformly spread over individual particles in moist snow. Comparison with measured snow backscatter by Wen et al (1990) at 17 GHz is enouraging. Calculated values follow the pattern of the data as a function of incidence angle but are consistently about 2 dB low. This may well be explained by the particle size distribution effects brought out in the later work.

Shi (1991) investigates SAR-oriented active polarimetry for snow from L to X band. Wet snow is accounted for primarily by assuming greatly increased extinction and a rougher surface due to melting. While wavelengths in the X band regime are only about one-third that at 35 GHz, one hopes that developments in connection with UW and MIT personnel will yield productive MMW applications.

While ice and snow are logically considered together, one must distinguish the particular problems associated with the former, especially when sea ice is considered. A wealth of detail on the phenomenology, physical, and theoretical questions should appear soon in a book edited by Carsey (1993). A chapter on theoretical modeling of sea ice microwave/MMW behavior recounts the testing of various contrasting models on three reasonably well characterized saline ice samples over a frequency range that approximately includes our span of interest. Any applicable model must somehow include the effects of elongated, oriented brine pockets or bubbles in the ice. Alternatively one can concentrate on the complementary shape of the individual crystals defining the boundaries of those pockets. Models tested (and their originators) were designated to include independent Rayleigh scattering layers (Drinkwater); dense media RT (UW); dense medium theory with integral equation method for rough surface (DMT-IEM by Fung and

coworkers); many layer strong fluctuation theory (SFT by Stogryn-Grenfell; polarimetric SFT (Nghiem/MIT); and MRT (Lee/Mudaliar). Particularly in certain aspects and certain frequency domains, successes are shown, while many questions remain. When published, this document should direct our attention to promising modeling techniques and topics for further investigation. As work already published in which our frequency is treated and successful comparisons to data are shown, we mention the work of Lee and Mudaliar (1988) and Mudaliar and Lee (1990).

## IV. AVAILABLE COMPUTER CODES

In this section information is provided on specific models and sources of models. Entries are listed by source and are grouped more or less by area of application. For each model or package, information is given on applications, model features and approach, and source contact. Commments on each include information such as location of reference discussion in the body of the report, limitations and advantages, and status of code testing and facilitation. In some instances considerations of code documentation, availability, ease of use, and support are subsumed in the category "code usability." Many notable models discussed above do not find mention below because they failed in some way to meet our general criteria for inclusion here (e.g. insufficient information from originators, complexity or resource requirements beyond feasibility limits, unavailability of code, lack of application testing against geophysical media, unlikely future support for the code, etc). This should not be interpreted as a negative judgment on the scientific validity or research value of such models.

### MPM

Features: Computes complex refractivity profiles together with power attenuation and propagation delay rates as functions of frequency, humidity, or pressure, for air with possible inclusion of water vapor, haze, fog/cloud, and rain.

Comments: See section III.2 in text. Input factors may be frequency, barometric pressure, RH, temperature, haze type, suspended water droplet concentration, and rain rate. In different versions of the model the user inputs a range for one of the first three variables and fixed values for some or all of the remaining ones. Rain treatment very simple. Easy to use code, with plentiful comments and references embedded.

Source/contract:

Dr. Hans J. Liebe
NTIA/ITS.S1
325 Broadway
Boulder, CO 80303
phone: 303-497-3310

ENHANCED RADTRAN

Features: Computes atmospheric attenuation and brightness temperature for typical atmospheric paths, including effects of clear air, fog, cloud, and rain, with polarized surface emissivities.

Comments: Improvements by AER of 1979 AFGL program (see section III.2 in text); core treatment of gas and aerosol effects are solid; newer RT algorithm treats multiple scattering from precipitation; formulations of terrestrial surface effects very approximate; limited validation of recent enhancements; code documented, disseminated, and supported; more extensive validation underway.

Contact/source:

Dr. Vincent J. Falcone
Geophysics Laboratory
Air Force Systems Command
United States Air Force
Hanscom AFB, MA 01731-5000
phone: 617-377-4029

Dr. Ronald G. Isaacs
Atmospheric & Environmental Research, Inc.
840 Memorial Drive
Cambridge, MA 02139
617-547-6207

GASIEWSKI RADIATIVE TRANSFER (GRT) MODEL

Features: Computes brightness temperature and associated statistics for planar stratified scattering atmospheres over specularly reflecting surfaces.

Comments: Iterative RT solution for temperature weighting functions, with absorbing atmosphere and Mie scattering from precipitation (see Section III.2 in text); very simple surface emissivity factors, with general user-specified (constant) bistatic scattering coefficient inclusion under development; as for RADTRAN polarimetric effects from precipitation generally lacking; aspherical hydrometeor formulation under development; code usability: "Undergraduate students at Georgia Tech have been able to obtain useful results from the model within a few hours."

Source/contact:

Prof. Al Gasiewski
Department of Electrical Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0250
phone: 404-894-2934

FUNG SURFACE MODEL

Features: Integrated and facilitated surface scattering model based on SPM, KA, or integral equation approach.

Comments: See discussion in section in section II.2 in text. PC oriented, user friendly software and documentation under development with anticipated completion by the present; user inputs choices of rms height, correlation length, and possibly correlation function, program displays results compared to user input data; subject to parameter field limits of each technique; integral equation approach most permissive, requiring primarily rms slope less than about 0.4.

Source/contact:

Professor Adrian Fung
University of Texas at Arlington
Arlington, TX 76019
phone: 817-273-3422

UPM SURFACE MODEL

Features: Unified perturbation method producing complete bistatic cross sections for E and H pol; Gaussian and power law surface spectra heretofore, others possible.

Comments: See section II.2 in text. Formulation reduces where appropriate to KA, SPM, and two-scale theories, with greater overall range of convergence but similar input requirements; 1-D roughness code available, 2-D nearing completion; possible inclusion of 1-D roughness finite element and method of moments codes for Monte Carlo simulation; bistatic results allow inference of reciprocal passive behavior; upcoming 2-D roughness treatment would allow fully polarimetric treatments possible integration with specific ocean modeling capability.

Source/contact:

Drs. Ernesto Rodriguez and
Yunjin Kim
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109
phone: 818-354-9500

GWU VEGETATION MODEL

features: WT based approach to sparse layer over half space with classes of scatterers having orientation distributions.

Comments: See section II.2 of text. Some ground-vegetation multi-bounce paths included, but overall the model treats two-layer single scattering theory with attentuation; KA treatment of rough ground surface; polarimetric backscatter coefficients calculated. Previously formulation and especially validation at frequencies no higher than C band, with recent developments oriented towards at least X band; model runs on IBM mainframe (3031) or HP Workstation (425t); documentation status unknown.

Source/contact:

Professor Roger Lang
Department of Electrical Engineering
and Computer Science
George Washington University
Washington, DC 20052
phone: 202-994-6083

SCHWERING AND JOHNSON VEGETATION MODEL

Features: Scalar RT treatment of vegetation field with surface but no deep boundary; computes propagation from which backscatter can be obtained.

Comments: See section II.2 in text; very simple model relying on measured or estimated two-parameter phase function; satisfactory simulation of data on which phase function was based; limited generality; program could be made available and documentation developed at small to moderate cost.

Source/contact:

Dr. Robert Johnson
Textron Defense Systems, MS 3106
201 Lowell St
Wilmington, MA 01887
phone: 508-657-1721

UW SNOW MODEL

Features: Computes polarimetric surface and volume scatter and emission from snowpacks under different moisture conditions.

Comments: See section III.4 in text; assumed spherical particles allow pair distribution function calculation and consequent dense medium approach; formulation includes particle size distribution with presence of moisture; developments anticipated in connection with MIT personnel and Shi from UCSB. Validation: encouraging. Code usability: potential. Documentation status: unknown. Continuing developments presently underway.

Source/contact:

Prof. Leung Tsang
Electromagnetics of Remote Sensing Lab
Department of Electrical Engineering
University of Washington
Seattle, WA 98195
phone: 206-685-7537

EMSARS

Features: EMSARS - Electromagnetic Model for Scattering Applied to Remote Sensing; general active and passive polarimetric computational package for generic anisotropic volume and surface scattering with layered media.

Comments: Single scattering WT for three non-dense random medium layers (free space, isotropic layer covering uniaxial random layer, ground); strong fluctuation theory for effective permittivities and distorted Born approximation for covariance matrix; surface scattering modules can treat perturbed quasi-periodic surface, reducing to classical two-scale random rough surface, or "classical" KA, GO, SPM, plus EBC for periodic surface; rough surface effect added incoherently. Integrated code and documentation exist with ongoing debugging; can be run on commonly available workstations; prospective union with UW dense medium/snow model, and integration of recent MMW sea ice code; importantly, integrated capability has been developed from GIS/map data through simulation to scene generation.

Source/contact:

Professor Jin Au Kong and Dr. Eric Yang
Center for Electromagnetic Theory
and Application
Research Laboratory of Electronics
MIT
Cambridge, MA 02139
phone: 617-253-8535

## V. REFERENCES


Borgeaud, M., J.A. Kong, and F.C. Lin (1986). Microwave remote sensing of snow-covered sea ice, Proc. IGARSS '86, pp133-138, Zurich.

Borel, C.B. and R.E. McIntosh (1990). Millimeter wave backscatter from deciduous trees, IEEE Trans. ATP, 38(9), 1391-1398.

Borel, C.C., R.E. McIntosh, R.M. Narayanan, and C.T. Swift (1986). File of normalized radar cross sections (FINRACS) - A computer program for research of the scattering of radar signals by natural surfaces, IEEE Trans. Geosci. Rem. Sens., 24(6), 1020-1022.

Carsey, F. (ed/author) (1993). Microwave Remote Sensing of Sea Ice, to appear.

Chandrasekhar, S. (1960). Radiative Transfer, Dover, NY.

Chauhan, N.S., R.H. Lang, and K.J. Ranson (1991). Radar modeling of a boreal forest, IEEE Trans. Geosci. Rem. Sens., 29(4), 627-638.

Chen, J.S. and A. Ishimaru (1990). Numerical simulation of the second-order Kirchhoff approximation from very rough surfaces and a study of backscattering enhancement, J. Acoust. Soc. Am., 88(4), 1846-1850.

Chen, M.F. and A.K. Fung (1988). A numerical study of the regions of validity of the Kirchhoff and small perturbation rough surface scattering models, Radio Sci., 23(2), 163-170.

Chuah, H.T., and H.S. Tan (1992a). A radar backscatter model for forest stands, Waves in Random Media, 2, 7-28.

__________ (1992b). A microwave emission model for vegetative medium using Monte Carlo method: part I, J. Electrmagn. Waves Applic., 6(7), 799-834.

__________ (1992c). A microwave emission model for vegetative medium using Monte Carlo method: part II, J. Electrmagn. Waves Applic., 6(7), 835-852.

Davis, J.L. et al (1992). TRACK 4.2: Radar cross section and tracking simulation users guide, GTRI, GIT, Atlanta, GA.

Ding, K.H., C.E. Mandt, L. Tsang, and J.A. Kong (1992). Monte Carlo simulations of pair distribution functions of dense discrete random media with multiple sizes of particle, J. Electromagn. Waves Applic., 6(8), 1015-1030.

Ding, K.H. and L. Tsang (1989). Effective propagation constants in media with densely distributed dielectric particles of multiple sizes and permittivities, Ch 3, PIER1, J.A. Kong (ed).

____________ (1991). Effective propagation constants and attenuation rates in media of densely distributed coated dielectric particles with size distributions, J. Electromagn. Waves Applic., 5(2), 117-142.

Falcone, V.J., Jr., L.W.Abreu, and E.P Shettle (1979). Atmospheric attenuation of millimeter and submillimeter waves: models and computer code, AFGL report TR-79-0253, Hanscom AFB, MA.

____________ (1982). Atmospheric attenuation in the 30 to 300 GHz region using RADTRAN and WMTRAN, SPIE Vol 337, MMW Technol., 62-66.

Faust, N.L, M.M. Horst, A.D. Sheffer, K.D. Vaughn, and M.S. West (1989). GTSPECS - multispectral sensor simulation, Proc. 2nd Nat'l Symp. Sensors and Sensor Fusion, Orlando, FL.

Fung, A.K., A.J. Blanchard, and M.F. Chen (1990). Polarization properties in random surface scattering, Ch.3 in PIER3, J.A. Kong (ed).

Fung, A.K., M.F. Chen, and K.K. Lee (1987). Fresnel field interaction applied to scattering from a vegetation layer, Rem. Sens. Environ., 23, 35-50.

Fung, A.K. and H.J. Eom (1985). A study of backscattering and emission from closely packed inhomogeneous media, IEEE Trans. Geosci. Rem. Sens., 23(5), 761-767.

Fung, A.K., Z. Li, and K.S. Chen (1992). Backscattering from a randomly rough dielectric surface, IEEE Trans. Geosci. Rem. Sens., 30(2), 356-369.

Fung, A.K. and G.W. Pan (1987). A scattering model for perfectly conducting random surface: I. Model development. II. Range of validity, Int'l. J. Rem. Sens., 8(11), 1579-1605.

Gasiewski, A.J. (1993). Microwave Radiative Transfer in Hydrometeors, Ch. 3 in <u>Atmospheric Remote Sensing by Microwave Radiometry</u>, (M.A. Janssen, ed). Wiley & Sons, to appear.

Gasiewski, A.J. and D.H. Staelin (1990). Numerical modeling of passive microwave $O_2$ observations over precipitation, Radio Sci., 25(3), 217-235.

Hallikainen, M.T., F.T. Ulaby, and T. E. van Deventer (1987). Extinction behavior of dry snow in the 18- to 90-GHz range, IEEE Trans. Geosci. Rem. Sens., 25(6), 737-745.

Honig, S.T. I. Sreenivasiah, and A. Ishimaru (1977). Plane wave pulse propagation through random media, IEEE Trans ATP, 25(6), 822-828.

Isaacs, R.G., M. Livshits, and R.D. Worsham (1988). Scattering properties of precipitation for the AFGL RADTRAN model, Appl. Opt., 27(1), 14-16.

Isaacs, R.G., S.A. Clough,and R.D. Worsham (1989a). The enhanced AFGL RADTRAN transmittance/brightness temperature computer code, SPIE Vol 1115 Propag. Engg., 243-253.

Isaacs, R.G., Y-A Jin, R.D. Worsham, G. Deblonde, and V.J. Falcone, Jr. (1989b). RADTRAN microwave surface emission models, IEEE Trans Geosci. Rem. Sens., 27(4), 433-440.

Isaacs, R.G., R.D. Worsham, and B.L. Lindner (1989b). Characterizing microwave propagation using the AFGL microwave attenuation/transmittance/ brightness temperature code, AFGL Report GL-TR-89-0188, Hanscom AFB, MA.

Ishimaru, A (1978). Wave Propagation and Scattering in Random Media, Vols I-II, NY: Academic Press.

Ishimaru, A. and J.S. Chen (1990). Scattering from very rough surfaces based on the modified second-order Kirchhoff approximation with angular and propagation shadowing, J. Acoust. Soc. Am., 88(4), 1877-1883.

Ishimaru, A., J.S. Chen, P. Phu, and K. Yoshitomi (1991). Numerical, analytical, and experimental studies of scattering from very rough surfaces and backscattering enhancement, Waves in Random Media, 1, S91-S107.

Ishimaru, A. and R. Cheung (1980). Multiple scattering effect on radiometric determination of rain attenuation at millimeter wavelengths, Radio Sci., 15(3), 507-516.

Ishimaru, A. and Y. Kuga (1982). Attenuation constant of a coherent field in a dense distribution of particles, J. Opt. Soc. Am., 72, 1317-1320.

Ishimaru, A., D. Lesselier, and C. Yeh (1984a). Multiple scattering calculations for nonspherical particles based on vector radiative transfer theory, Radio Sci., 19(5), 1356-1366.

Ishimaru, A., and K.J. Painter (1980). Backscattered pulse shape due to small-angle multiple scattering in random media, Radio Sci., 1591), 87-93.

Ishimaru, A., C. Yeh, and D. Lesselier (1984b). First-order multiple scattering theory for nonspherical particles, Appl. Opt., 23(22), 4132-4139.

Jin, J.A. and R.G. Isaacs (1987). Simulation and statistical retrieval for inhomogeneous nonisothermal atmospheric precipitation, J. Quant. Spectroscop. Radiat. Transfer, 37(5), 461-469.

Johnson, R.A., and F. Schwering (1985). A transport theory of millimeter wave propagation in woods and forests, US Army CECOM, Fort Monmouth NH., R&D Tech. Rep. DECOM-TR-85-1.

Karam, M.A. and A.K. Fung (1988). Electromagnetic scattering from a layer of finite length, randomly oriented, dielectric, circular cylinders over a rough interface with application to vegetation, Int. J. Rem. Sens., 9(6), 1109-1134.

_____________ (1989). Leaf shape effects in electromagnetic scattering from vegetation, IEEE Trans. Geosci. Rem. Sens., 21(6), 687-697.

Kim, Y., E. Rodriquez, and S. Durden (1992). Numerical assessment of rough surface scattering theories: vertical polarization, Radio Sci., in press.

Kong, J.A. (1986). Electromagnetic Wave Theory, Wiley-Interscience, NY.

__________ (1989). Progress in Electromagnetics Research (PIER1), Elsevier, NY.

__________ (1990). PIER3, Elsevier, NY

Kong, J.A., R.T. Shin, J.C. Shiue, and L. Tsang (1979). Theory and experiment for passive microwave remote sensing of snowpacks, JGR, 84(B10), 5669-5673.

Kuga, Y. (1991). Third and four-order iterative solution for the vector radiative transfer equation, J. Opt. Soc. Am. A., 8(10), 1580-1586.

Kuga, Y., F.T. Ulaby, T.F. Haddock, and R.D. DeRoo (1991). Millimeter-wave radar scattering from snow: 1. Radiative transfer model, Radio Sci., 26(2), 329-341.

Lang, R.H. (1981). Electromagnetic backscattering from a sparse distribution of lossy dielectric scatterers, Radio Sci., 16(1), 15-30.

Lang, R.H. and O. Kavaklioglu (1991). MMW Scattering from needle arrays, APS/URSI Symposium, London, Ontario, Canada.

Lang, R.H. and J.S. Sidhu (1983). Electromagnetic backscattering from a layer of vegetation: a discrete approach, IEEE Trans. Geosci. Rem. Sens., GE21(1), 62-71.

Lang, R.H. and O. Yazici (1989). Electromagnetic backscattering from a layer of random discs in the small wavelength limit, abstract in proc. Progr. in Electromagn. Res. Symp. 1989, Cambridge, MA.

Lee, J.K. and J.A. Kong (1988). Modified radiative transfer theory for a two-layer anisotropic random medium, J. Electromagn. Waves Applic., 2, 391-424.

Lee, J.K. and S. Mudaliar (1988). Backscattering coefficients of a half-space anisotropic random medium by the multiple scattering theory, Radio Sci., 23(3), 429-442.

LeVine, D.M., R. Meneghini, R.H. Lang, and S.S. Seker (1983). Scattering from arbitrarily oriented dielectric disks in the physical optics regime, J. Opt. Soc. Am., 73(10), 1255-1262.

Liebe, H.J. (1989). MPM - An atmospheric millimeter-wave propagation model, Int. J. Infrared MM Waves, 10(6), 631-650.

__________ (1992). Atmospheric spectral properties between 10 and 350 GHz: new laboratory measurements and models, Specialists Mtg Microw. Radiom. Rem. Sens., Boulder, CO.

Liebe, H.J., T. Manabe, and G.A. Hufford (1989). Millimeter-wave attenuation and delay rates due to fog/cloud conditions, IEEE Trans ATP, 37(12), 1617-1623.

Liu, H.L and A.K. Fung (1988). An empirical model for polarized and cross-polarized scattering from a vegetation layer, Rem. Sens. Environ., 25, 23-36.

Lou, S.H., L. Tsang, C.H. Chan, and A. Ishimaru (1991). Application of the finite element method to Monte Carlo simulations of scattering of waves by random rough surfaces with periodic boundary conditions, J. Electromagn. Waves Applic., 5(8), 835-855.

Manabe, J.T., R.O. DeBolt, and H.J. Liebe (1989). Moist-air attenuation at 96 GHz over a 21-km line-of-sight path, IEEE Trans. Geosci. Rem. Sens., 37(2), 262-266.

Mudaliar, S. and J.K. Lee (1990). Microwave scattering and emission from a half-space anisotropic random medium, Radio Sci., 25(6), 1199-1210.

McMillan, R.W., R.A. Bohlander, G.R. Ochs, R.J. Hill, S.F. Clifford, D.G. Bauerle, and J. Nemarich (1982). Millimeter wave atmospheric turbulence measurements: preliminary results, SPIE Vol 337 MMW Technol., 88-95.

Narayanan, R.M. and R.E. McIntosh (1990). Millimeter-wave backscatter characteristics of multilayered snow surfaces, IEEE Trans ATP, 38(5), 693-703.

Nghiem, S.V. Electromagnetic Wave Models for Polarimetric Remote Sensing of Geophysical Media, (1991). PhD Thesis, MIT.

Nghiem, S.V., M. Borgeaud, J.A. Kong, and R.T. Shin (1990). Polarimetric remote sensing of geophysical media with layer random medium model, Ch.1 in PIER3, J.A. Kong (ed).

Peifer, J.W., R.B. Rakes, M.S. West, and J.H. Andrews (1988). MAX - Geometrical data base editor users manual, GTRI, GIT, Atlanta, GA.

Pickle, J.D., R.G. Isaacs, M.K. Griffin, V.J. Falcone, J.F. Morrissey, R. Kakar, and J. Wang (1993). Comparison of co-located SSM/T-2 and MIR mesurements: results from the calibration study, Conf. Passive Infr. Rem. Sens. Cloud Atmos., Orlando FL, Apr 1993, SPIE Proc. 1934.

Rodriguez, E. and Y. Kim (1992). A unified perturbation approach for rough surface scattering, Radio Sci., 27, 79-93.

Rodriguez, E., Y. Kim, and S. Durden (1992). Numerical assessment of rough surface scattering theories: horizontal polarization, Radio Sci., in press.

Rodriguez, E., Y. Kim, and J.M. Martin (1992). The effect of small-wave modulation on the electromagnetic bias, JGR, 97(C2), 2379-2389.

Saatchi, S.S., R.H. Lang, and D.M. LeVine (1991). Microwave backscattering and emission for grass canopies, IGARSS 91, Helsinki, Finland.

Sarabandi, K, T.B.A. Senior, and F.T. Ulaby (1988). Effect of curvature on the backscattering from a leaf, J. Electromagn. Waves Applic., 2(7), 653-670.

Sarabandi, K., F.T. Ulaby, and T.B.A. Senior (1990). Millimeter wave scattering model for a leaf, Radio Sci., 25(1), 9-18.

Senior, T.B.A., K. Sarabandi, and F.T. Ulaby (1987). Measuring and modeling the backscattering cross section of a leaf, Radio Sci., 22(6), 1109-1116.

Schwering, F. and R.A. Johnson (1986). A transport theory of millimeter wave propagation in woods and forests, J. wave-material interaction, 1, 205-235.

Schwering, F., E.J. Violette, and R.H. Espeland (1988). Millimeter-wave propagation in vegetation: experiments and theory, IEEE Trans. Geosci. Rem. Sens., 26(3), 355-367.

Shi, J. (1991). Radar polarimetric modeling and observations of snow-covered terrain, Ph.D. Thesis, UCSB

Shin, R.T. and J.A. Kong (1982). Theory for thermal microwave emission from a homogeneous layer with rough surfaces containing spherical scatterers, JGR, V87, NB7, 5566-5576.

________________ (1989). Radiative Transfer Theory for Active Remote Sensing of Two-layer Random Medium, Ch. 5 in PIER1, J.A. Kong (ed).

Tavakoli, A., K. Sarabandi, and F.T. Ulaby (1991). Horizontal propagationn through periodic vegetation canopies, IEEE Trans. ATP, 39(7), 1014-1023.

Thorsos, E.I. (1988). The validity of the Kirchhoff approximation for rough surface scattering using a Guassian roughness spectrum, J. Acoust. Soc. Am, 83(1), 78-92.

Tsang, L (1991). Polarimetric passive microwave remote sensing of random discrete scatterers and rough surfaces, J. Electromagn. Waves Applic., 5(1), 41-57.

Tsang, L. and K.H. Ding (1991). Polarimetric signatures of a layer of random nonspherical discrete scatterers overlying a homogeneous half space based on first and second order vector radiative transfer theory, IEEE Trans. Geosci. Rem. Sens., 29(2), 242-253.

Tsang, L., C.H. Chan, J.A. Kong, and J. Joseph (1992a). Polarimetric signatures of a canopy of dielectric cylinders based on first and second order vector radiative transfer theory, J. Electromagn. Waves Applic., 6(1), 19-51.

Tsang, L., K.H. Ding, and B. Wen (1990). Polarimetric signature of random discrete scatterers based on vector radiative transfer theory, Ch. 3, PIER3, J.A. Kong (ed).

Tsang, L. and A Ishimaru (1987). Radiative wave equations for vector electromagnetic propagation in dense nontenuous media, J. Electromagn. Waves Applic., 1(1), 52-72.

Tsang, L. and J.A. Kong (1976). Microwave remote sensing of a two-layer random medium, IEEE Trans. Antennas Propagat., AP-24, 283-288.

________________ (1992). Scattering of electromagnetic waves from a dense medium consisting of correlated Mie scatterers with size distributions and applications to dry snow, J. Electromagn. Waves Applic., 6(3), 265-286.

Tsang, L., J.A. Kong, and R.T. Shin (1985). Theory of Microwave Remote Sensing, Wiley-Interscience, NY.

Tsang, L., C. Mandt, and K.H. Ding (1992b). Monte Carlo simulations of the extinction rate of dense media with randomly distributed dielectric spheres based on solutions of Maxwell's equations," Opt. Lett., 17(5), 314-316.

Ulaby, F.T. and M.C. Dobson (1989a). <u>Handbook of Radar Scattering Statistics for Terrain</u>, Artech House, 357 pp.

________________ (1989b). Radar Scattering Statistics for Terrain: Software and User's Manual, Artech House, 79 pp & 3 computer disks.

Ulaby, F.T. and T.F. Haddock (1990). Millimeter Wave Radar Scattering from Terrain: Data Handbook (Version 2), U. MI Techn. Rep. 026247-4-T, 206 pp.

Ulaby, F.T., T.F. Haddock, and Y. Kuga (1990). Measurement and modeling of millimeter-wave scattering from tree foliage, Radio Sci., 25(3), 193-203.

Ulaby, F.T., T.F. Haddock, R.T. Austin, and Y. Kuga (1991). Millimeter wave radar scattering from snow: 2. Comparison of theory with experimental observations, Radio Sci., 26(2), 343-351.

Ulaby, F.T., R.K. Moore, and A.K. Fung (1982). Radar Remote Sensing and Surface Scattering and Emission Theory, Vol II in <u>Microwave Remote Sensing</u>, Addison-Wesley, Reading MA.

__________ (1986). From Theory to Application, Vol III in <u>Microwave Remote Sensing</u>, by Ulaby et al, op cit.

Ulaby, F.T., T.E. van Deventer, J.R. East, T.F. Haddock, and M.E. Coluzzi (1988). Millimeter-wave bistatic scattering from ground and vegetation, IEEE Geosci. Rem. Sens., 26(3), 229-243.

Violette, E.J., R.H. Espeland, R.O. DeBolt, and F.W. Schwering (1988). Millimeter-wave propagation at street level in an urban environment, IEEE Trans. Geosci. Rem. Sens., 26(3), 368-380.

Weinman, J.A. (1989). A Rayleigh-Gans model of millimeter wave scattering by randomly oriented snowflakes, SPIE Propag. Engg, 387-394.

Wen, B., L. Tsang, D.P. Winebrenner, and A. Ishimaru (1990). Dense medium radiative transfer theory: comparisons with experiment and application to microwave remote sensing and polarimetry, IEEE Trans. Geosci. Rem. Sens., 28(1), 46-59.

Winebrenner, D.P. and A. Ishimaru (1985). Application of the phase perturbation technique to randomly rough surfaces, J. Opt. Soc. Am, 2(12), 2285-2294.

Yueh, S.H., J.A. Kong, J.K. Jao, R.T. Shin, H.A. Zebker, and T. LeToan (1991). K-distribution and multifrequency polarimetric terrain radar clutter, J. Electromagn. Waves Applic., 5(1), 1-15.

Yueh, S.H., J.A. Kong, J.K. Jao, R.T. Shin, and T. L. Toan (1992). Branching model for vegetation, IEEE Trans. Geosci. Rem. Sens., 30(2), 390-402.

# VI. APPENDIX

## MAY 13-15, 1992, MMW MODELING WORKSHOP PARTICIPANTS:

Dr. KEVIN O'NEILL (Moderator)
USACRREL
72 Lyme Rd
Hanover, NH 03755

Dr. JAMES (PAT) WELSH
SWOE Program Manager
SWOE Program Office
USACRREL
72 Lyme Rd
Hanover, NH 03755

Prof. ADRIAN FUNG
University of Texas at Arlington
Arlington, TX 76019

Prof. AL GASIEWSKI
Department of Electrical Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0250

Dr. RONALD ISAACS
Atmospheric & Environmental Research Inc.
840 Memorial Drive
Cambridge, MA 02139

Prof. AKIRA ISHIMARU
Electromagnetics of Remote Sensing Laboratory
Department of Electrical Engineering
University of Washington
Seattle, WA 98195

Dr. JUNJIN KIM
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109

Prof. JIN AU KONG
Center for Electromagnetic Theory and Applications
Research Laboratory of Electronics
Room 26-305
MIT
Cambridge, MA 02139

Prof. ROGER LANG
Department of Electrical Engineering and Computer Science
George Washington University
Washington, DC 20052

Dr. HANS LIEBE
NTIA/ITS.S1
325 Broadway
Boulder, CO 80303

Mr. STEVE LOHMEIER
Microwave Remote Sensing Laboratory
University of Massachussetts
Amherst, MA 01003

Prof. ROBERT MCINTOSH
Microwave Remote Sensing Laboratory.
University of Massachussetts
Amherst, MA 01003

Prof. LEUNG TSANG
Electromagnetics of Remote Sensing Laboratory
Department of Electrical Engineering
University of Washington
Seattle, WA 98195

Dr. ERIC YANG
Center for Electromagnetic Theory and Applications
Research Laboratory of Electronics
MIT
Cambridge, MA 02139

# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



| 1. AGENCY USE ONLY (Leave Blank) | 2. REPORT DATE | 3. REPORT TYPE AND DATES COVERED |
|---|---|---|
| | May 1993 | |

4. TITLE AND SUBTITLE

A Review of Millimeter Wave Modeling

5. FUNDING NUMBERS

6. AUTHORS

Kevin O'Neill

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Cold Regions Research and Engineering Laboratory
Hanover, New Hampshire

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

SWOE Program Office
U.S. Army Cold Regions Research and Engineering Laboratory
Hanover, New Hampshire 03755-1290

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

SWOE Report 93-1

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

A survey was undertaken of models available for millimeter wave (MMW) scattering and emission from environmental features, particularly at 35 and 94 GHz. The ultimate objective was to identify validated models for implementation in scene generation tasks for the Smart Weapons Operability Enhancement Program. The ideal model would be based on first principles, would be readily available in facilitated software, and would have reasonable requirements in terms of computational resources and input parameters. At MMW frequencies, these requirements push the frontiers of current science and technology. In most applications, one must accept as a first approximation the approaches currently under development in research settings. This report reviews the basic methods and approaches underlying all available models in terms of volume scattering, treatment of surfaces and transitions, and the development of statistical quantities from rational physics. Very rough surfaces, locally steep surface slopes, and low angle incidence can rarely be treated successfully. Promise has been shown recently in using the Unified Perturbation Method to treat multi-scale ocean roughness in terms of pure surface scattering. Volume and combined surface/volume scattering and emission models are reviewed here for applications in vegetation, snow, and ice environments. Most are essentially works in progress, with theory and validation currently building from earlier work at C and X bands. Very sound capabilities are available for treatment of common atmospheric features, with recent progress in modeling more complex meteorological events. Limiting consideration to truly available codes, a list is provided of models and their sources for each of the above areas. Because it is the most comprehensive and is currently facilitated in terms of software, the EMSARS model is the foremost candidate to serve as a platform for future addition and development.

14. SUBJECT TERMS

| | | |
|---|---|---|
| MMW Modeling | Geometric Modeling | Information Bases |
| Rendering | Validation | |

15. NUMBER OF PAGES

55

16. PRICE CODE

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | Same as Report |